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CMS Collaboration ; Canelli, M F ; Chiochia, V ; Kilminster, B ; Robmann, P ; et al

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Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for new physics is performed in multijet events with large missing transverse momentum produced in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$ using a data sample corresponding to an integrated luminosity of $19.5\,\text{fb}^{-1}$ collected with the CMS detector at the LHC. The data sample is divided into three jet multiplicity categories (3–5, 6–7, and $\geq$8 jets), and studied further in bins of two variables: the scalar sum of jet transverse momenta and the missing transverse momentum. The observed numbers of events in various categories are consistent with backgrounds expected from standard model processes. Exclusion limits are presented for several simplified supersymmetric models of squark or gluino pair production.

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*See Appendix A for the list of collaboration members

1 Introduction

The standard model of particle physics (SM) successfully describes a wide variety of observations in high energy physics. The recent discovery of a new scalar boson with a mass of about 125 GeV [1–3] at the CERN Large Hadron Collider (LHC) marks another success for the SM, as its properties measured so far are consistent with those of the long-sought Higgs boson. However, its mass is predicted to be unstable against quadratically divergent quantum-loop corrections, which suggests the presence of physics beyond the SM. Supersymmetry (SUSY) is a well-explored extension that addresses various shortcomings of the SM. SUSY postulates a new symmetry, relating fermionic and bosonic degrees of freedom, and introduces a superpartner for each SM particle. Radiative corrections due to SUSY particles can compensate the contribution of the SM particles and thereby stabilize the mass of the Higgs boson. In R-parity-conserving models [4], SUSY particles are produced in pairs, and the lightest SUSY particle (LSP) is stable. If weakly interacting and neutral, the LSP is a potential dark matter candidate.

This paper reports an inclusive search for physics beyond the SM in multijet events with large missing transverse momentum produced in pp collisions at a centre-of-mass energy $\sqrt{s} = 8\,\mathrm{TeV}$ at the LHC. The data sample used corresponds to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$ collected by the Compact Muon Solenoid (CMS) experiment [5]. This final state is motivated by many extensions of the SM, for example those given in Refs. [6–8]. At the LHC, both the CMS and ATLAS collaborations have performed SUSY searches in all-hadronic final states [9–17]. For all these searches, the observed numbers of events were consistent with the expected SM background, and exclusion limits were set in the context of the constrained minimal supersymmetric extension of the standard model (CMSSM) [18–20] and various simplified models [21, 22]. Contrary to the CMSSM case, the masses of particles are free parameters in simplified models, thus allowing a generic study of the parameter space of SUSY and SUSY-like theories. Simplified models of squark and gluino pair production are used to interpret the search results in this paper.

This analysis follows previous inclusive searches [9, 10] that require at least three jets in the final state. These searches are most sensitive to the hypothetical production of pairs of squarks and gluinos, where the squarks (gluinos) each decay to one (two) jets and an undetected LSP. We extend the analyses of Refs. [9, 10] by subdividing the data into three exclusive jet multiplicity categories: N_{Jets} = 3–5, 6–7, and $\geq$8, which renders the analysis more sensitive to a variety of final-state topologies resulting from longer cascades of squarks and gluinos, and hence in a larger number of jets. The search regions with higher jet multiplicities extend the sensitivity of the analysis to models in which the gluino often decays into top quarks. While other analyses exploit the presence of bottom-quark jets in signal events to discriminate against background [12, 13], this analysis follows a complementary strategy by requiring a large number of jets, thus helping to keep the signal efficiency for fully hadronic final states as high as possible.

The events in each jet multiplicity category are further divided according to variables that characterize the total visible hadronic activity (H_{T}) and the momentum imbalance ($\not\!\!H_{\mathrm{T}}$) in an event, both defined in the plane transverse to the beam. Due to the presence of a number of energetic jets and two LSPs in the final state, the signal events are expected to have large H_{T} and $\not\!\!H_{\mathrm{T}}$. The main SM processes contributing to this final state are Z+jets events, where the Z boson decays to a pair of neutrinos ($\mathrm{Z}(\nu\bar{\nu})$+jets), and W+jets and $\mathrm{t\bar{t}}$ events, where a W boson decays to an e, μ, or τ lepton ($\mathrm{W}(\ell\nu)$+jets). The presence of at least one neutrino in these events provides a source of genuine $\not\!\!H_{\mathrm{T}}$. Another background category is quantum chromodynamics (QCD) multijet events with large $\not\!\!H_{\mathrm{T}}$ from leptonic decays of heavy-flavour hadrons inside the jets, jet energy mismeasurement, or instrumental noise and non-functioning detector components.

All these backgrounds are determined using the data, with as little reliance on simulation as possible.

2 The CMS detector and event reconstruction

The CMS detector is a multipurpose apparatus, described in detail in Ref. [5]. The CMS coordinate system is defined with the origin at the centre of the detector and the z axis along the anticlockwise beam direction. The polar angle θ is measured with respect to the z axis, and the azimuthal angle ϕ (measured in radians) in the plane perpendicular to that axis. Charged-particle trajectories are measured with a silicon pixel and strip tracker, covering $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$. Immersed in the 3.8 T magnetic field provided by a 6 m diameter superconducting solenoid, which also encircles the calorimeters, the tracking system provides transverse momentum (p_{T}) resolution of approximately 1.5% for charged particles with $p_{\mathrm{T}} \sim 100\,\mathrm{GeV}$. A lead-tungstate crystal electromagnetic calorimeter and a brass-and-scintillator hadron calorimeter surround the tracking volume and cover the region $|\eta| < 3$. Steel and quartz-fibre hadron forward calorimeters extend the coverage to $|\eta| \leq 5$. Muons are identified in gas ionization detectors embedded in the steel flux return yoke of the magnet. The events used for this search are recorded using a two-level trigger system described in Ref. [5].

The recorded events are required to have at least one well-identified interaction vertex with z position within 24 cm from the nominal centre of the detector and transverse distance from the z axis less than 2 cm. The primary vertex is the one with the largest sum of p_{T}-squared of all the associated tracks, and is assumed to correspond to the hard-scattering process. The events are reconstructed using a particle-flow (PF) algorithm [23]. This algorithm reconstructs a list of particles in each event, namely charged and neutral hadrons, photons, muons, and electrons, combining the information from the tracker, the calorimeters, and the muon system. These particles are then clustered into jets using the anti-k_{T} clustering algorithm [24] with a size parameter of 0.5. Contributions from additional pp collisions overlapping with the event of interest (pileup) are mitigated by discarding charged particles not associated with the primary vertex and using the Fastjet tools [25, 26] to account for the neutral pileup component. Corrections to jet energy are applied to account for the variation of the response in p_{T} and η [27]. Missing transverse momentum ($\not\!\!E_{\mathrm{T}}$) is reconstructed as magnitude of the vector sum of p_{T} of all the reconstructed PF particles [28, 29].

3 Sample selection

The search regions are first defined using a loose baseline selection with the following requirements:

- $N_{\mathrm{Jets}} \geq 3$, where N_{Jets} is the number of jets with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ and $|\eta| < 2.5$.
- $H_{\mathrm{T}} > 500\,\mathrm{GeV}$, with $H_{\mathrm{T}} = \sum_{\mathrm{jets}} p_{\mathrm{T}}$, where the sum includes all jets with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ and $|\eta| < 2.5$.
- $\not\!\!H_{\mathrm{T}} > 200\,\mathrm{GeV}$, with $\not\!\!H_{\mathrm{T}} = |\vec{\not\!\!H}_{\mathrm{T}}| = |-\sum_{\mathrm{jets}} \vec{p}_{\mathrm{T}}|$, where in this case, jets are required to satisfy $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 5$.
- $|\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{Jet1}}, \vec{\not\!\!H}_{\mathrm{T}})| > 0.5$, $|\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{Jet2}}, \vec{\not\!\!H}_{\mathrm{T}})| > 0.5$, and $|\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{Jet3}}, \vec{\not\!\!H}_{\mathrm{T}})| > 0.3$, vetoing the events where $\vec{\not\!\!H}_{\mathrm{T}}$ is aligned with one of the three highest p_{T} jets. This requirement rejects most of the QCD multijet events in which a single mismeasured jet yields high $\not\!\!H_{\mathrm{T}}$.

- Events containing isolated muons or electrons with $p_{\mathrm{T}} > 10$ GeV are vetoed in order to reject $\mathrm{t\bar{t}}$ and W/Z+jets events with leptons in the final state. Both the e and μ are required to produce a good quality track that is matched to the primary interaction vertex [30, 31]. The isolation is measured as the scalar p_{T} sum of PF particles ($p_{\mathrm{T}}^{\mathrm{sum}}$), except the lepton itself, within a cone of width $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ for e (0.4 for μ) around the lepton. The $p_{\mathrm{T}}^{\mathrm{sum}}$ is required to be less than 20% (15%) of the p_{T} of the e (μ).
- In addition, events affected by instrumental effects, particles from non-collision sources, or poorly reconstructed kinematic variables are rejected (event cleaning) [28, 29]. Events are also rejected if a jet with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ has more than 95% of its energy from PF photon candidates or more than 90% from PF neutral hadron candidates.

The data sample used for this analysis was collected using trigger algorithms that required events to have $H_{\mathrm{T}} > 350\,\mathrm{GeV}$ and $\not{E}_{\mathrm{T}} > 100\,\mathrm{GeV}$. The trigger efficiencies are measured to be greater than 99% for the offline baseline selection of $H_{\mathrm{T}} > 500\,\mathrm{GeV}$ and $\not{H}_{\mathrm{T}} > 200\,\mathrm{GeV}$ in all jet multiplicity categories used in this search. A sample of 11 753 events is selected after applying the baseline criteria. The selected events are divided into 36 non-overlapping search regions defined in terms of N_{Jets}, H_{T}, and $\not{H}_{\mathrm{T}}$, as listed in the first three columns of Table 1.

Several Monte Carlo (MC) simulation samples are used to model the signal as well as to develop and validate the background estimation methods. The $\mathrm{t\bar{t}}$, W/Z+jets, γ+jets, and QCD multijet background samples are produced using the MADGRAPH5 [32] generator at leading order (LO), interfaced with the PYTHIA 6.4.24 [33] parton-shower model, and scaled to the next-to-leading order (NLO) or next-to-next-to-leading order cross section predictions [34, 35]. The events are processed through a GEANT4 simulation of the detector [36]. The SUSY signal samples are generated using MADGRAPH5, the CTEQ6L [37] parton distribution functions (PDF), and are simulated using the CMS fast simulation package [38]. The underlying event description used for the MC simulated samples is described in Ref. [39]. The effect of pileup interactions is included by adding a number of simulated minimum bias events, on top of the hard interaction, to match the distribution observed in data.

4 Background estimation

In this search, all backgrounds are measured from data using methods similar to those described in Refs. [9, 10]. The $\mathrm{Z}(\nu\bar{\nu})$+jets background is estimated using γ+jets events, exploiting their electroweak correspondence to Z+jets production for boson p_{T} above $\sim$100 GeV. The Z+jets and γ+jets events exhibit similar characteristics, apart from electroweak coupling differences and asymptotically vanishing residual mass effects. The $\mathrm{t\bar{t}}$ or $\mathrm{W}(\ell\nu)$+jets events satisfy the search selection when the e/μ is not identified or isolated, or is out of the detector acceptance ("lost-lepton" background) or when a τ lepton decays hadronically (τ_{h} background). The lost-lepton background is estimated by reweighting events in a μ+jets data control sample with measured lepton efficiencies. The estimation of the τ_{h} background starts from a similar μ+jets sample, replacing the muon with a jet sampled as a function of jet p_{T} from τ_{h} templates obtained from simulation. The QCD multijet background is measured using a "rebalance-and-smear" method [9, 10]. The kinematical characteristics of multijet events are predicted from data by applying a fitting procedure that imposes zero missing transverse momentum on each event, and then smearing the jets according to data-corrected jet energy resolution values. The relative contribution of the various backgrounds varies in the different search regions.

4.1 Estimation of $Z(\nu\overline{\nu})$ +jets background

Photons and Z bosons exhibit similar kinematic properties at high p_{T}, and therefore the hadronic component of an event containing either a high-p_{T} photon or Z boson is similar [40–43]. The γ+jets sample used to evaluate the $Z(\nu\overline{\nu})$+jets event rate is collected by triggering on events with a γ candidate and large H_{T}. The photon candidates are reconstructed using the energy deposited in the electromagnetic calorimeter [44, 45]. Photon candidates with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$ and $|\eta| < 1.44$ or $1.566 < |\eta| < 2.5$ are used in this analysis, and are required to have their lateral shower profile consistent with that of a photon produced in the hard-scattering process (a prompt photon). To veto electrons misidentified as photons, the candidates with an associated track in the pixel detector are rejected. A photon candidate is required to satisfy tight isolation requirements based on the sum over p_{T} values of the PF candidates that lie within a cone of radius $\Delta R = 0.3$ around the direction of its momentum.

The contribution to the γ+jets control sample from events in which the photon candidate originates from the misidentification of jet fragments (background photons) is measured using a template method, which exploits the difference between the shower profile of prompt (signal) and background photons, using the distribution of a modified second moment of the electromagnetic energy cluster around its mean η position [44]. The distribution (template) for background events is obtained from a sideband region defined by selecting photons that satisfy very loose photon identification and isolation requirements but fail the stringent isolation requirements. The distribution for signal events is obtained from simulation. The sum of the two templates is fit to the observed distribution, with the normalization (background and signal yields) of each template determined in the fit. On average, 93% of selected γ+jets candidate events are determined to originate from prompt photons.

To mimic the missing momentum due to the neutrinos from the decay of the Z boson, the photon candidate is not included in the calculation of H_{T} and $\not{H}_{\mathrm{T}}$ for the γ+jets events. The number of $Z(\nu\overline{\nu})$+jets events is then estimated by correcting the number of γ+jets events for photon acceptance and reconstruction efficiency, and scaling the result with the ratio relating the production cross section of the two processes ($R_{Z/\gamma}$) in the various search regions. Therefore, the ratio $R_{Z/\gamma}$, which we derive from simulation, is studied as a function of H_{T}, $\not{H}_{\mathrm{T}}$, and N_{Jets} using events generated with MADGRAPH (up to four partons) that are processed through the PYTHIA parton shower algorithm to generate additional jets. The ratio exhibits a strong dependence on $\not{H}_{\mathrm{T}}$ for values below around 500 GeV (Fig. 1(a)), but changes by only $(12 \pm 5)\%$ as H_{T} varies between 500 and 1500 GeV (Fig. 1(b)), which is the region of interest to this search. The ratio is parametrized as a linear function of N_{Jets} in several $\not{H}_{\mathrm{T}}$ ranges, $200 < \not{H}_{\mathrm{T}} < 300\,\mathrm{GeV}$, $300 < \not{H}_{\mathrm{T}} < 450\,\mathrm{GeV}$, and $\not{H}_{\mathrm{T}} > 450\,\mathrm{GeV}$, as shown in Fig. 1(c). The predicted numbers of $Z(\nu\overline{\nu})$ +jets events and uncertainties for various search regions are summarized in Table 1.

The theoretical uncertainty associated with $R_{Z/\gamma}$ is estimated using $Z(\mu^+\mu^-)$ +jets events selected from data and simulation, by requiring two opposite-sign muons to satisfy the muon selection and to form an invariant mass within $\pm 20\,\mathrm{GeV}$ of the Z boson mass. The double ratio of $R_{Z(\mu^+\mu^-)/\gamma}$ using events from data to those from simulation is parametrized as a function of N_{Jets} using a linear function, as shown in Fig. 1(d), and is used to correct $R_{Z/\gamma}$ for a given jet multiplicity. The fitting procedure results in uncertainties of 20%, 25%, and 45% for the background predicted in the search regions with N_{Jets} = 3–5, 6–7, and $\geq$8, respectively. The difference in the modeling of photon identification and isolation in the simulation and data leads to uncertainties of 2–5%, 10–20%, and 20–25% on the estimated number of $Z(\nu\overline{\nu})$+jets events for the three jet multiplicity intervals, respectively. The subtraction of events with non-prompt photons from QCD multijet events amounts to less than a 5% uncertainty for the final

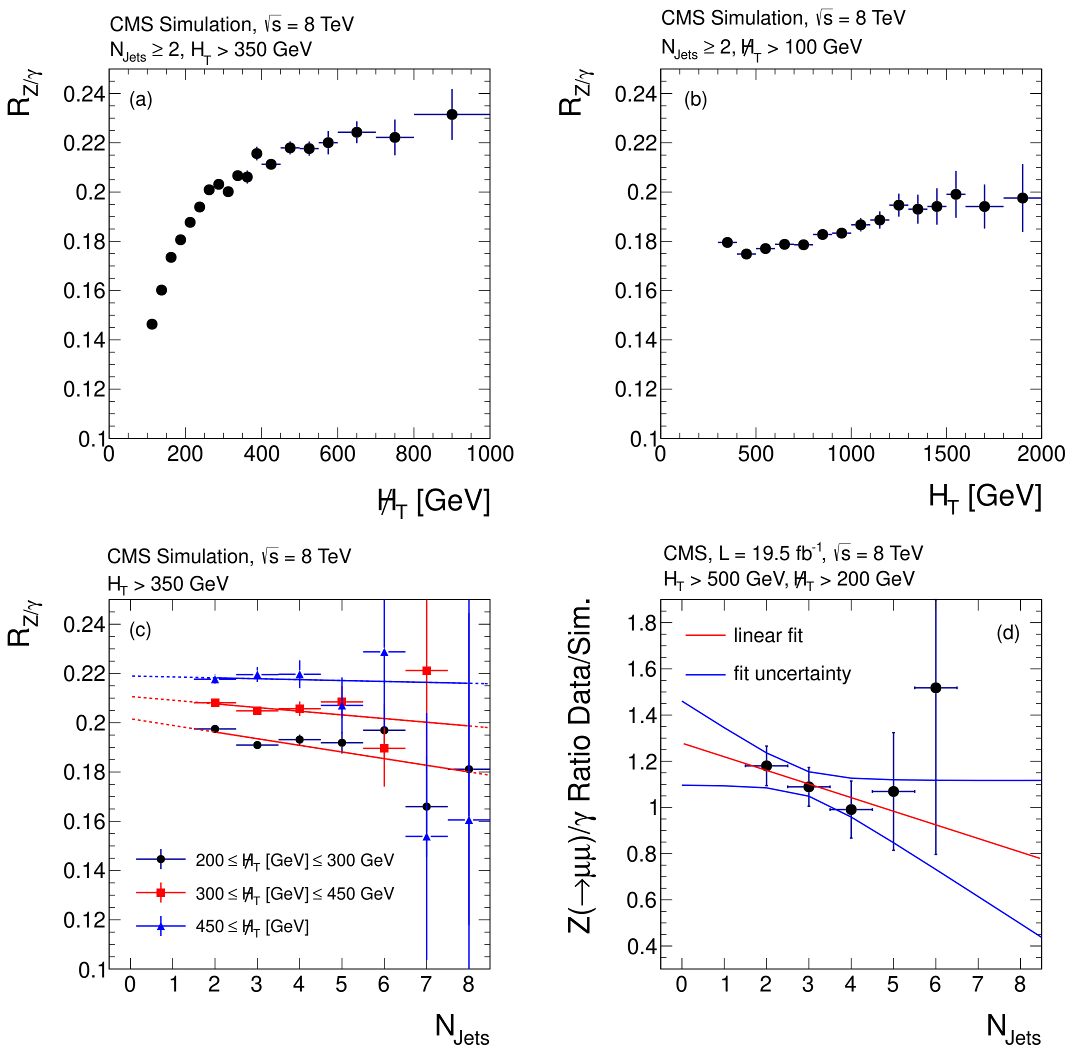

Figure 1: The simulated ratio $R_{Z/\gamma}$ as a function of (a) $\not\!\!H_{\mathrm{T}}$, (b) H_{T}, (c) N_{Jets}, where the values for three $\not\!\!H_{\mathrm{T}}$ bins are shown with linear fits, and (d) the double ratio of $R_{Z(\mu^+\mu^-)/\gamma}$, using events from data to those from simulation; the linear fit and its uncertainty band are overlaid.

background prediction.

4.2 Estimation of the lost-lepton background

The lost-lepton background is estimated from a μ+jets control sample, selected with the same criteria as used for the search, except that events are required to have exactly one well-reconstructed and isolated μ with $p_{\mathrm{T}}^{\mu} > 10\,\mathrm{GeV}$. The events are collected with the same trigger that is used to search for the signal. The transverse mass $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\mu} \not\!\!E_{\mathrm{T}} [1 - \cos(\Delta\phi)]}$ is required to be less than 100 GeV in order to select events containing $\mathrm{W} \to \mu\nu$ decays as well as to reject possible signal events. Here $\Delta\phi$ is the azimuthal angle between the $\vec{p}_{\mathrm{T}}{}^{\mu}$ and the $\vec{\not\!\!E}_{\mathrm{T}}$ directions.

Using the reconstruction and isolation efficiencies $\epsilon_{\mathrm{reco}}^{\mathrm{e},\mu}$ and $\epsilon_{\mathrm{iso}}^{\mathrm{e},\mu}$ of the electrons and muons, the events in the isolated muon control sample are weighted by $(1/\epsilon_{\mathrm{iso}}^{\mu}) \times [(1 - \epsilon_{\mathrm{reco}}^{\mathrm{e},\mu})/\epsilon_{\mathrm{reco}}^{\mu}]$ in order to estimate the number of events with unidentified leptons, and by $(\epsilon_{\mathrm{reco}}^{\mathrm{e},\mu}/\epsilon_{\mathrm{reco}}^{\mu}) \times [(1 - \epsilon_{\mathrm{iso}}^{\mathrm{e},\mu})/\epsilon_{\mathrm{iso}}^{\mu}]$ to estimate the number of events with non-isolated leptons in the signal region. The predicted number of lost-lepton events is corrected to account for the detector and kinematic acceptance of the muons. The lepton efficiencies and kinematic acceptance factors are obtained from the MC simulation of W+jets and $\mathrm{t\bar{t}}$ events and are determined in bins of N_{Jets}, H_{T}, and $\not\!\!H_{\mathrm{T}}$.

This method is validated using simulated $\mathrm{t\bar{t}}$ and W+jets events. The single-muon events selected from the simulated samples are used to predict the number of background events expected in the zero-lepton search regions. The resulting H_{T}, $\not\!\!H_{\mathrm{T}}$, and N_{Jets} distributions are compared in Fig. 2 to the genuine ones obtained from $\mathrm{t\bar{t}}$ and W+jets events simulated at the detector level. The predicted distributions closely resemble the genuine ones.

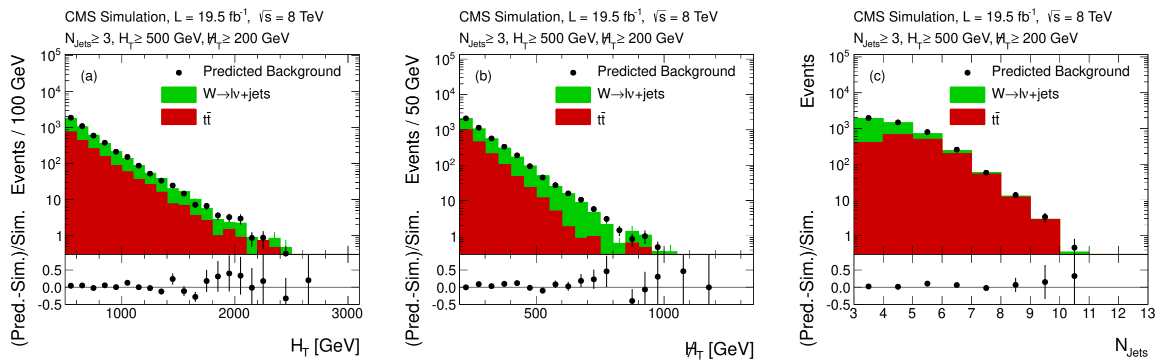

Figure 2: Predicted (a) H_{T}, (b) $\not\!\!H_{\mathrm{T}}$, and (c) N_{Jets} distributions found from applying the lost-lepton background evaluation method to simulated $\mathrm{t\bar{t}}$ and W+jets events (solid points) in comparison to the genuine $\mathrm{t\bar{t}}$ and W+jets background from simulation (shaded curves). Only statistical uncertainties are shown.

The number of lost-lepton events predicted from data using the method described above, and the corresponding uncertainties, are listed in Table 1 for each search region. The dominant uncertainties arise from the limited number of single-muon events in most of the search regions. The differences in lepton reconstruction and isolation efficiencies between data and MC simulation are evaluated using a "tag-and-probe" method [46] on $\mathrm{Z}(\mu^+\mu^-)$+jets events. The lepton reconstruction and isolation efficiencies are measured in bins of lepton p_{T} and ΔR relative to the closest jet. This method renders these efficiencies insensitive to the kinematic differences between $\mathrm{Z}(\ell^+\ell^-)$+jets events and $\mathrm{t\bar{t}}$ and W+jets events. Relative differences between the predictions using efficiencies extracted from data and MC simulation result in 10–25%, 10–30%, and 15–24% uncertainties for the predicted background for various H_{T} and $\not\!\!H_{\mathrm{T}}$ search bins with

N_{Jets} = 3–5, 6–7, and $\geq$8, respectively. An additional uncertainty of 15% for N_{Jets} = 3–5 and 40% for $N_{\text{Jets}} \geq 6$ is assigned based on the statistical precision of the validation of this background estimation method. Variation of the PDFs following the procedure of Ref. [47] affects the muon acceptance, and leads to an uncertainty of less than 4% on the final prediction. Any mismodeling of anomalous $\not{E}_{\text{T}}$ [28] affects the simulated m_{T} and results in 3% uncertainty for the predicted lost-lepton background.

4.3 Estimation of the hadronic τ lepton background

The τ_{h} background is estimated from a sample of μ+jets events, selected with an inclusive single μ or $\mu + \geq$2-jet trigger, by requiring exactly one μ with $p_{\text{T}} > 20\,\text{GeV}$ and $|\eta| < 2.1$. As in the estimation of the lost-lepton background, only events with $m_{\text{T}} < 100\,\text{GeV}$ are considered. The μ+jets and τ_{h} +jets events arise from the same physics processes; hence the hadronic component of the two samples is the same aside from the response of the detector to a muon or a τ_{h} jet. To account for this difference, the muon is replaced by a simulated τ_{h} jet, whose p_{T} value is randomly sampled from an MC response function, $p_{\text{T}}^{\text{Jet}}/p_{\text{T}}^{\tau}$. Here, the p_{T}^{τ} is the transverse momentum of a generated hadronically decaying τ lepton selected from simulated $\text{t}\bar{\text{t}}$ and $\text{W}(\tau\nu)$+jets events and $p_{\text{T}}^{\text{Jet}}$ is that of a reconstructed jet matching the τ lepton in η–ϕ space. In order to sample the response function completely, this procedure is repeated one hundred times for each event. The N_{Jets}, H_{T}, and $\not{H}_{\text{T}}$ values of the events are recalculated, now including this τ_{h} jet, and search region selection criteria are applied to predict the τ_{h} background. The predicted background is corrected for the trigger efficiency, muon selection efficiency, kinematic and detector acceptance, and the ratio of branching fractions $\mathcal{B}(\text{W} \to \tau_{\text{h}}\nu)/\mathcal{B}(\text{W} \to \mu\nu) = 0.6476 \pm 0.0024$ [48]. The muon isolation and reconstruction efficiencies are obtained from MC simulation of W+jets and $\text{t}\bar{\text{t}}$ events in bins of lepton p_{T} and ΔR relative to the closest jet. To account for the difference in efficiencies measured in data and MC simulation, the predicted numbers of τ_{h}+jets events are corrected by 4.9%, 4.7%, and 3.5% for N_{Jets} =3–5, 6–7, and $\geq$8, respectively. The predicted τ_{h} background and uncertainties are shown in Table 1 for all the search regions.

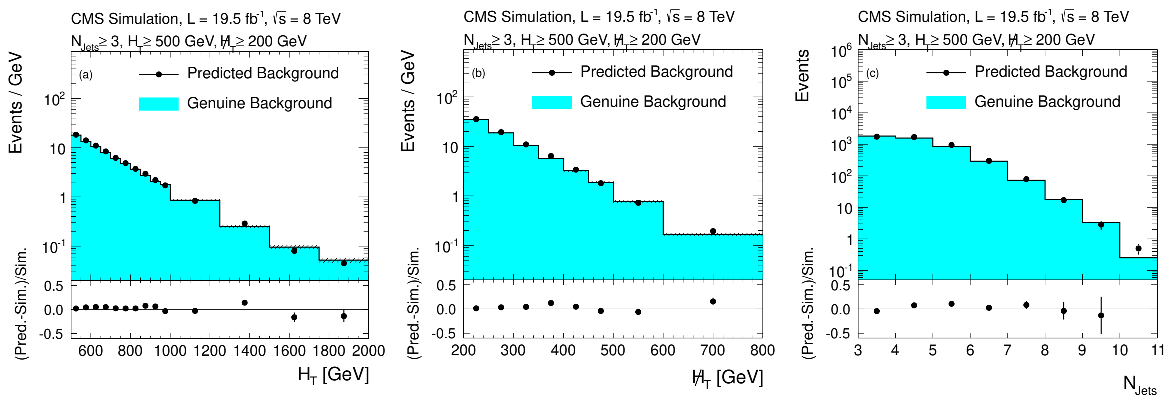

Figure 3: Predicted (a) H_{T}, (b) $\not{H}_{\text{T}}$, and (c) N_{Jets} distributions found from applying the τ_{h} background evaluation method to simulated $\text{t}\bar{\text{t}}$ and W+jets events (solid points) in comparison to the genuine $\text{t}\bar{\text{t}}$ and W+jets background from simulation (shaded curve). Only statistical uncertainties are shown.

The τ_{h} background estimation method is validated by applying it to simulated W+jets and $\text{t}\bar{\text{t}}$ MC samples. The results are shown in Fig. 3 in comparison to the genuine τ_{h} background from the simulated events. To evaluate the performance of the method for events with varying hadronic activity, the method is validated in each search bin. Uncertainties of 10%, 20%, and 20% are assigned to the predicted rates for events with N_{Jets} =3–5, 6–7, and $\geq$8 respectively, mainly to reflect the level of statistical precision for this validation. Due to the multiple sampling of the response template, the statistical uncertainty of the prediction is evaluated with a set of pseudo-experiments using a bootstrap technique [49]. Relative differences between the predictions using efficiencies extracted from data and MC result in 2–20% uncertainties across the various search bins. Other systematic uncertainties arise from the geometrical and kinematic acceptance for the muons (3%), and the τ-jet response function (1–15%). An uncertainty of 1–8% is assigned to account for possible differences between data and MC simulation for the acceptance of the m_{T} selection.

4.4 Estimation of the QCD multijet background

The background from QCD multijet events is evaluated with the "rebalance and smear" method [9, 10], using data samples recorded with H_{T} thresholds ranging from 350 to 650 GeV. The events, recorded with a trigger prescaled by a factor k, are sampled k times to create seed events as described below.

In the rebalance step, the momenta of the jets with $p_{\mathrm{T}} > 10\,\mathrm{GeV}/c$ in each event are adjusted within the jet-p_{T}-resolution values, using a kinematic fit, such that the events are balanced in the transverse plane. Considering only jets with p_{T} above a certain threshold introduces an additional imbalance in the event, which results in larger p_{T} for the rebalanced jets than the expected true value. This effect is compensated by scaling the rebalanced jets by a p_{T}-dependent factor derived by comparing rebalanced and generator-level jets in the simulation. The scaling factors derived using either PYTHIA or MADGRAPH, and with different average pileup interactions, are found to be similar. The jets in the rebalanced events are then smeared using jet p_{T} response functions, which are obtained from MC simulation as a function of p_{T} and η, and adjusted to match those determined from dijet and γ+jets data [27]. The QCD multijet background is predicted by applying selection criteria on the kinematic quantities calculated from the smeared jets. The procedure is repeated one hundred times to evaluate the average prediction and its statistical uncertainty in each search region.

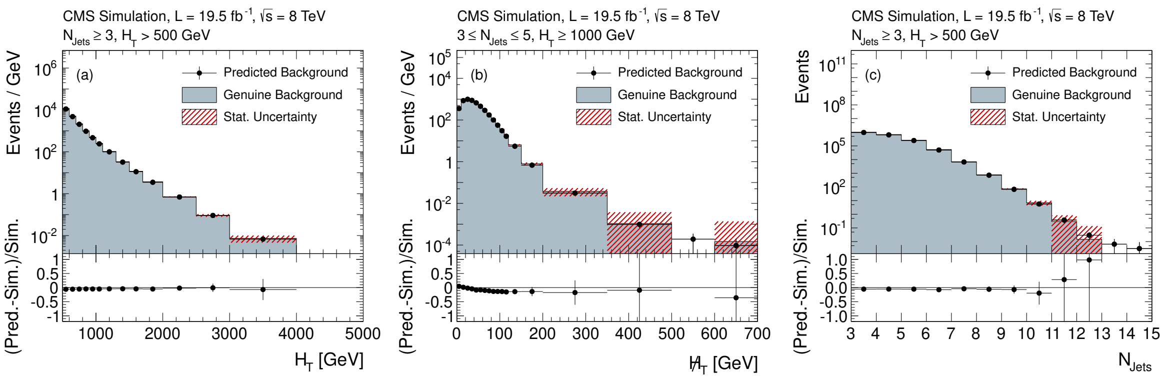

Figure 4: Predicted (a) H_{T}, (b) $H\!\!\!/_{\mathrm{T}}$, and (c) N_{Jets} distributions found from applying the "rebalance-and-smear" method to simulated QCD multijet events (solid points) in comparison with the genuine QCD multijet background from simulation (shaded curve). The distributions are shown for events that satisfy the baseline selection, except that the $H\!\!\!/_{\mathrm{T}}$ selection is not applied, and in addition $H_{\mathrm{T}} > 1000\,\mathrm{GeV}$ is required for the events used in the $H\!\!\!/_{\mathrm{T}}$ distribution. The statistical uncertainties are indicated by the hatched band for the expectation and by error bars for the prediction.

The method is validated using simulated QCD multijet events. Comparisons of the H_{T}, $H\!\!\!/_{\mathrm{T}}$, and N_{Jets} distributions from the MC simulation to those predicted by the rebalance-and-smear method on the same simulated events are shown in Fig. 4. A systematic uncertainty of 11–86% is assigned based on the statistical precision attributed to the validation procedure, which is performed both in the search regions and in QCD-enriched data control regions defined either by $100 < \not{H}_{\mathrm{T}} < 200\,\mathrm{GeV}$ or by inverting the $|\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{Jet1,2,3}}, \vec{\not{H}}_{\mathrm{T}})|$ selection. Due to the limited number of events in individual search bins, this uncertainty is evaluated for each jet multiplicity bin for H_{T} smaller or larger than 1000 GeV, inclusive over $\not{H}_{\mathrm{T}}$. The uncertainty due to differences in the core and tails of the jet response functions between data and simulation results in uncertainties of 10–30% and 20–35%, respectively. An uncertainty of 3%, 8%, and 35% is assigned for search regions with N_{Jets} = 3–5, 6–7, and ≥8, respectively, to account for the effect of pileup. The predicted QCD multijet background contributions to the search bins along with associated uncertainties are given in Table 1.

5 Results and interpretation

The predicted background event yields and the number of observed events are summarized in Table 1 and Fig. 5 for the 36 search regions. The data are consistent with the expected background contributions from SM processes. A slight excess of events is observed in the search bin with $N_{\mathrm{Jets}} = 6$–7, $H_{\mathrm{T}} = 500$–800 GeV, and $\not{H}_{\mathrm{T}} > 450\,\mathrm{GeV}$, which is insignificant when the probability to observe a statistical fluctuation as large or larger in any of the search regions is considered.

The results are interpreted in the context of simplified models [21, 22] of pair production of squarks ($\widetilde{\mathrm{q}}$) or gluinos ($\widetilde{\mathrm{g}}$). These particles decay directly, or via intermediate new particles, to quarks and an LSP, where the LSP is denoted as $\widetilde{\chi}_1^0$ in the following. The signal events are generated at LO using MADGRAPH5, with up to two additional partons. The cross sections are determined at NLO and include the resummation of soft gluon emission at the accuracy of next-to-leading-log (NLL) calculations [50–55]. Both for the generation of signal events and the calculation of $\widetilde{\mathrm{q}}$ ($\widetilde{\mathrm{g}}$) production cross section, the contribution of $\widetilde{\mathrm{g}}$($\widetilde{\mathrm{q}}$) production is effectively removed by assuming the gluino (squark) mass to be very large.

Several decay modes of gluinos are considered here, $\widetilde{\mathrm{g}} \to \mathrm{q}\overline{\mathrm{q}} + \widetilde{\chi}_1^0$, $\widetilde{\mathrm{g}} \to \mathrm{t}\overline{\mathrm{t}} + \widetilde{\chi}_1^0$, and $\widetilde{\mathrm{g}} \to \mathrm{q}\overline{\mathrm{q}} + \widetilde{\chi}^{\pm}/\widetilde{\chi}_2^0$ where $\widetilde{\chi}_1^{\pm} \to \mathrm{W} + \widetilde{\chi}_1^0$ and $\widetilde{\chi}_2^0 \to \mathrm{Z} + \widetilde{\chi}_1^0$. The branching fraction for the different decay modes is assumed, in turn, to be 100%, except for the $\widetilde{\mathrm{g}} \to \mathrm{q}\overline{\mathrm{q}} + \widetilde{\chi}$ process, where the decay proceeds via $\widetilde{\chi}_1^+$, $\widetilde{\chi}_1^-$ and $\widetilde{\chi}_2^0$ particles with equal probability. Squark production is studied in the decay mode $\widetilde{\mathrm{q}} \to \mathrm{q} + \widetilde{\chi}_1^0$. The models are studied in the parameter space of the mass of the LSP versus the mass of the gluino or squark. The $\not{H}_{\mathrm{T}}$ distributions observed for the three intervals of jet multiplicity are shown in Fig. 6 in comparison to the SM background prediction. The $\not{H}_{\mathrm{T}}$ distributions expected from gluino or squark pair production are overlaid for $m_{\widetilde{\mathrm{g}}} = 1.1$ TeV and $m_{\widetilde{\chi}_1^0} = 125\,\mathrm{GeV}$, and for $m_{\widetilde{\mathrm{q}}} = 700\,\mathrm{GeV}$ and $m_{\widetilde{\chi}_1^0} = 100\,\mathrm{GeV}$, in various decay modes.

The 95% confidence level (CL) upper limits on the signal production cross section are set using the LHC-style $\mathrm{CL_s}$ criterion [56–58]. The signal acceptance and efficiencies, and corresponding uncertainties for the 36 exclusive search regions, along with the background estimates discussed above, are combined into a likelihood that is used to construct the test statistic based on the profile likelihood ratio. The uncertainties of the signal acceptance and efficiency due to several sources are taken into account when cross section upper limits are determined. The uncertainties due to the luminosity determination (2.6%) [59], trigger inefficiency (2%), and event cleaning procedure (3%) [28] are the same for all signal models and search regions. The uncertainty from the measurement of the jet energy scale and jet energy resolution [27] leads to uncertainties of 2–8% and 1–2% in signal acceptance. The variation of PDFs [47] results in 1–

Table 1: Predicted event yields for the different background components in the search regions defined by H_T, $\not{H}_T$ and N_{Jets}. The uncertainties of the different background sources are added in quadrature to obtain the total uncertainties.

Selection			$Z \to \nu\bar{\nu}$	$t\bar{t}/W$	$t\bar{t}/W$	QCD	Total	Data
N_{Jets}	H_T [GeV]	$\not{H}_T$ [GeV]		$\to e,\mu$+X	$\to \tau_h$+X		background	
3–5	500–800	200–300	1820±390	2210±450	1750±210	310±220	6090±670	6159
3–5	500–800	300–450	990±220	660±130	590±70	40±20	2280±270	2305
3–5	500–800	450–600	273±63	77±17	66.3±9.5	$1.3^{+1.5}_{-1.3}$	418±66	454
3–5	500–800	>600	42±10	9.5±4.0	5.7±1.3	$0.1^{+0.3}_{-0.1}$	57.4±11.2	62
3–5	800–1000	200–300	216±46	278±62	192±33	92±66	777±107	808
3–5	800–1000	300–450	124±26	113±27	84±12	9.9±7.4	330±40	305
3–5	800–1000	450–600	47±11	36.1±9.9	24.1±3.6	$0.8^{+1.3}_{-0.8}$	108±15	124
3–5	800–1000	>600	35.3±8.8	9.0±3.7	10.3±2.0	$0.1^{+0.4}_{-0.1}$	54.8±9.7	52
3–5	1000–1250	200–300	76±17	104±26	66.5±9.9	59±25	305±41	335
3–5	1000–1250	300–450	39.3±8.9	52±14	41±11	5.1±2.7	137±20	129
3–5	1000–1250	450–600	18.1±4.7	6.9±3.2	6.8±2.0	$0.5^{+0.7}_{-0.5}$	32.3±6.1	34
3–5	1000–1250	>600	17.8±4.8	2.4±1.8	2.5±0.8	$0.1^{+0.3}_{-0.1}$	22.8±5.2	32
3–5	1250–1500	200–300	25.3±6.0	31.0±9.5	21.3±4.1	31±13	109±18	98
3–5	1250–1500	300–450	16.7±4.3	10.1±4.4	13.7±7.1	2.3±1.6	42.8±9.5	38
3–5	1250–1500	>450	12.3±3.5	2.3±1.7	2.7±1.2	$0.2^{+0.5}_{-0.2}$	17.6±4.1	23
3–5	>1500	200–300	10.5±2.9	16.7±6.2	23.5±5.6	35±14	86±17	94
3–5	>1500	>300	10.9±3.1	9.7±4.3	6.6±1.4	2.4±2.0	29.7±5.8	39
6–7	500–800	200–300	22.7±6.4	133±59	117±25	18.2±9.2	290±65	266
6–7	500–800	300–450	9.9±3.2	22±11	18.0±5.1	1.9±1.7	52±12	62
6–7	500–800	>450	0.7±0.6	$0.0^{+3.2}_{-0.0}$	$0.1^{+0.5}_{-0.1}$	$0.0^{+0.1}_{-0.0}$	$0.8^{+3.3}_{-0.6}$	9
6–7	800–1000	200–300	9.1±3.0	56±25	46±11	13.1±6.6	124±29	111
6–7	800–1000	300–450	4.2±1.7	10.4±5.5	12.0±3.6	1.9±1.4	28.6±6.9	35
6–7	800–1000	>450	1.8±1.0	2.9±2.5	1.2±0.8	$0.1^{+0.4}_{-0.1}$	6.0±2.8	4
6–7	1000–1250	200–300	4.4±1.7	24±12	29.5±7.8	11.9±6.0	70±16	67
6–7	1000–1250	300–450	3.5±1.5	8.0±4.7	8.6±2.7	1.5±1.5	21.6±5.8	20
6–7	1000–1250	>450	1.4±0.8	$0.0^{+3.6}_{-0.0}$	$0.6^{+0.8}_{-0.6}$	$0.1^{+0.4}_{-0.1}$	$2.2^{+3.8}_{-1.1}$	4
6–7	1250–1500	200–300	3.3±1.4	11.5±6.5	6.4±2.7	6.8±3.9	28.0±8.2	24
6–7	1250–1500	300–450	1.4±0.8	3.5±2.6	3.5±1.9	$0.9^{+1.3}_{-0.9}$	9.4±3.6	5
6–7	1250–1500	>450	0.4±0.4	$0.0^{+2.5}_{-0.0}$	$0.1^{+0.5}_{-0.1}$	$0.1^{+0.3}_{-0.1}$	$0.5^{+2.6}_{-0.4}$	2
6–7	>1500	200–300	1.3±0.8	10.0±6.9	2.0±1.2	7.8±4.0	21.1±8.1	18
6–7	>1500	>300	1.1±0.7	3.2±2.8	2.8±1.9	$0.8^{+1.1}_{-0.8}$	7.9±3.6	3
≥8	500–800	>200	$0.0^{+0.8}_{-0.0}$	1.9±1.5	2.8±1.4	$0.1^{+0.4}_{-0.1}$	$4.8^{+2.3}_{-2.1}$	8
≥8	800–1000	>200	0.6±0.6	4.8±2.9	2.3±1.2	$0.5^{+0.9}_{-0.5}$	$8.3^{+3.4}_{-3.3}$	9
≥8	1000–1250	>200	0.6±0.5	$1.4^{+1.5}_{-1.4}$	2.9±1.3	$0.7^{+1.0}_{-0.7}$	$5.6^{+2.3}_{-2.1}$	8
≥8	1250–1500	>200	$0.0^{+0.9}_{-0.0}$	5.1±3.5	1.4±0.9	$0.5^{+0.9}_{-0.5}$	$7.1^{+3.8}_{-3.6}$	5
≥8	>1500	>200	$0.0^{+0.7}_{-0.0}$	$0.0^{+4.2}_{-0.0}$	2.4±1.4	$0.9^{+1.3}_{-0.9}$	$3.3^{+4.7}_{-1.7}$	2

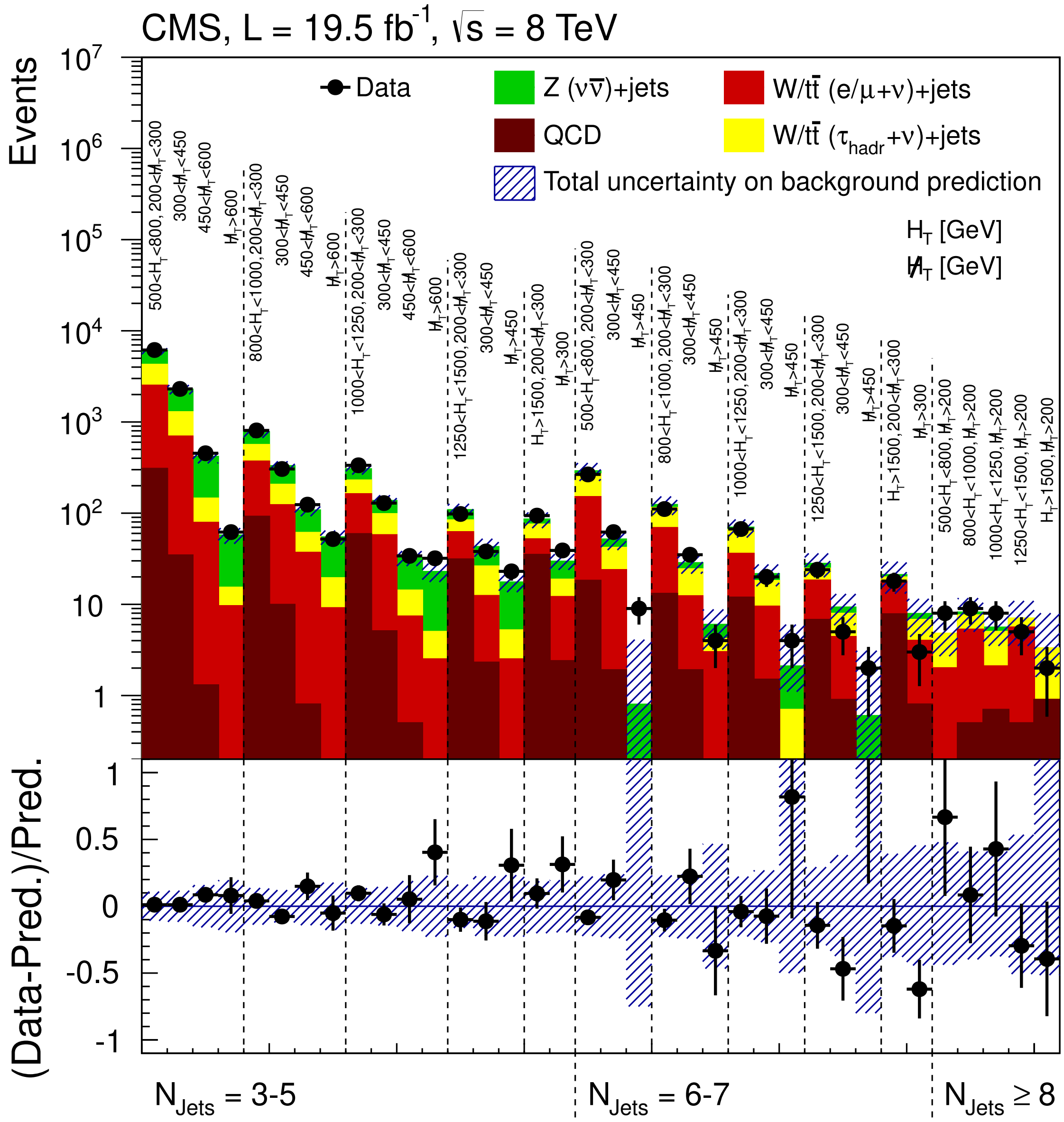

Figure 5: Summary of the observed number of events in each of the 36 search regions in comparison to the corresponding background prediction. The hatched region shows the total uncertainty of the background prediction.

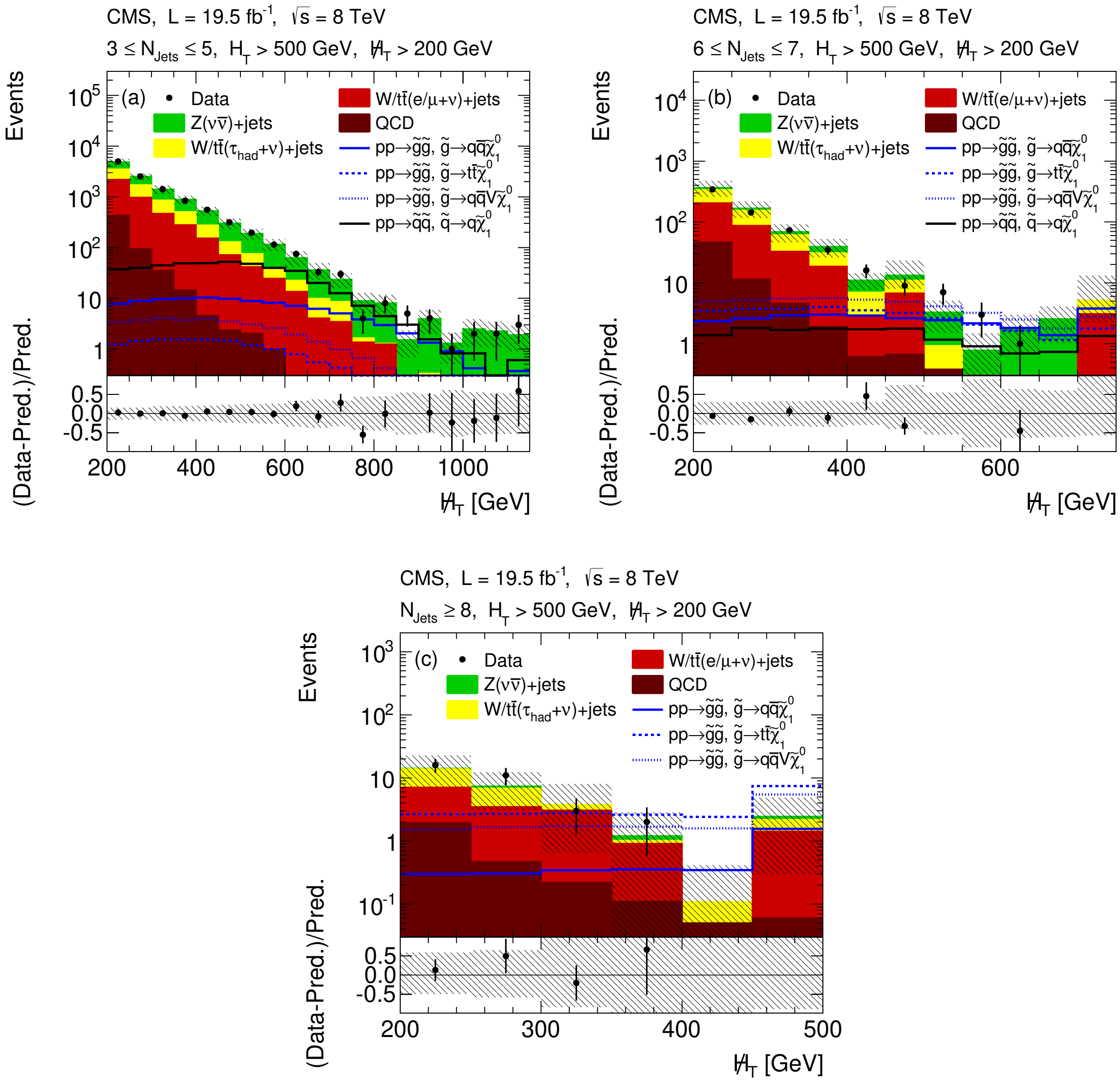

Figure 6: Observed $\not{H}_{\mathrm{T}}$ distributions compared to the predicted backgrounds for search regions with $H_{\mathrm{T}} > 500\,\mathrm{GeV}$ and jet multiplicity intervals of (a) 3–5, (b) 6–7, and (c) ≥ 8. The background distributions are stacked. The last bin contains the overflow. The hatched region indicates the uncertainties of the background predictions. The ratio of data to the background is shown in the lower plots. The $\not{H}_{\mathrm{T}}$ distributions expected from events with $\tilde{g}$ and $\tilde{q}$ pair production, with either $m_{\tilde{g}} = 1.1\,\mathrm{TeV}$ and $m_{\tilde{\chi}^0_1} = 125\,\mathrm{GeV}$ or $m_{\tilde{q}} = 700\,\mathrm{GeV}$ and $m_{\tilde{\chi}^0_1} = 100\,\mathrm{GeV}$, are overlaid.

8% uncertainty from the signal acceptance. The rate of initial-state radiation in the signal event simulation is corrected to correspond to that measured in data [60], leading to a corresponding uncertainty of 22% for model points with small differences between the masses of the gluino or squark and the $\widetilde{\chi}^0_1$. For larger mass differences, this uncertainty is typically less than a few percent.

The observed and expected 95% CL upper limits on the signal cross section are shown for the production of a $\widetilde{q}\widetilde{q}$ pair with $\widetilde{q} \to q + \widetilde{\chi}^0_1$ in Fig. 7(a), a $\widetilde{g}\widetilde{g}$ pair with $\widetilde{g} \to q\overline{q} + \widetilde{\chi}^0_1$ in Fig. 7(b), a $\widetilde{g}\widetilde{g}$ pair with $\widetilde{g} \to t\overline{t} + \widetilde{\chi}^0_1$ in Fig. 7(c), and a $\widetilde{g}\widetilde{g}$ pair with $\widetilde{g} \to q\overline{q} + W/Z + \widetilde{\chi}^0_1$ in Fig. 7(d), in the ($m_{\widetilde{q}}$, $m_{\widetilde{\chi}^0_1}$) and ($m_{\widetilde{g}}$, $m_{\widetilde{\chi}^0_1}$) planes. The contours show the exclusion regions for the signal production cross sections obtained using the NLO+NLL calculations. The exclusion contours are also presented when the signal cross section is varied by changing the renormalization and factorization scales by a factor of two and using the PDF uncertainty based on the CTEQ6.6 [61] and MSTW2008 [62] PDF sets. Conservatively, by comparing the observed limit to the theoretical cross section minus its one-standard-deviation uncertainty, for the cases where the gluino decays as $\widetilde{g} \to q\overline{q} + \widetilde{\chi}^0_1$, $\widetilde{g} \to t\overline{t} + \widetilde{\chi}^0_1$, and $\widetilde{g} \to q\overline{q} + W/Z + \widetilde{\chi}^0_1$, gluino masses up to 1.16, 1.13, and 1.21 TeV are excluded, respectively, for $m_{\widetilde{\chi}^0_1} < 100\,\mathrm{GeV}$. For direct $\widetilde{q}\widetilde{q}$ production of the first two generations of squarks ($\widetilde{u}_{L/R}$, $\widetilde{d}_{L/R}$, $\widetilde{c}_{L/R}$, $\widetilde{s}_{L/R}$), values of $m_{\widetilde{q}}$ below 780 GeV are excluded for $m_{\widetilde{\chi}^0_1} < 200\,\mathrm{GeV}$. If only one of these squarks is light, then $m_{\widetilde{q}}$ values below 400 GeV are excluded for $m_{\widetilde{\chi}^0_1} < 80\,\mathrm{GeV}$. The expected search sensitivity is improved with respect to our similar analysis [10] based on the 7 TeV data set by up to about 200 GeV in the values of $m_{\widetilde{g}}$, $m_{\widetilde{q}}$ and $m_{\widetilde{\chi}^0_1}$.

6 Summary

An inclusive search for supersymmetry has been performed in multijet events with $N_{\mathrm{Jets}} = 3$–5, 6–7, and $\geq$8, and large missing transverse momentum. The data sample corresponds to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$ collected in 8 TeV pp collisions during the year 2012 with the CMS detector at the LHC. The analysis extends the supersymmetric parameter space explored by searches in the all-hadronic final state. The observed numbers of events are found to be consistent with the expected standard model background, which is evaluated from the data. The results are presented in the context of simplified models, where final states are described by the pair production of new particles decaying to one, two, or more jets and a weakly interacting stable neutral particle, e.g. the lightest supersymmetric particle (LSP). Squark masses below 780 GeV and gluino masses of up to 1.1–1.2 TeV are excluded at 95% CL within the studied models for LSP masses below 100 GeV.

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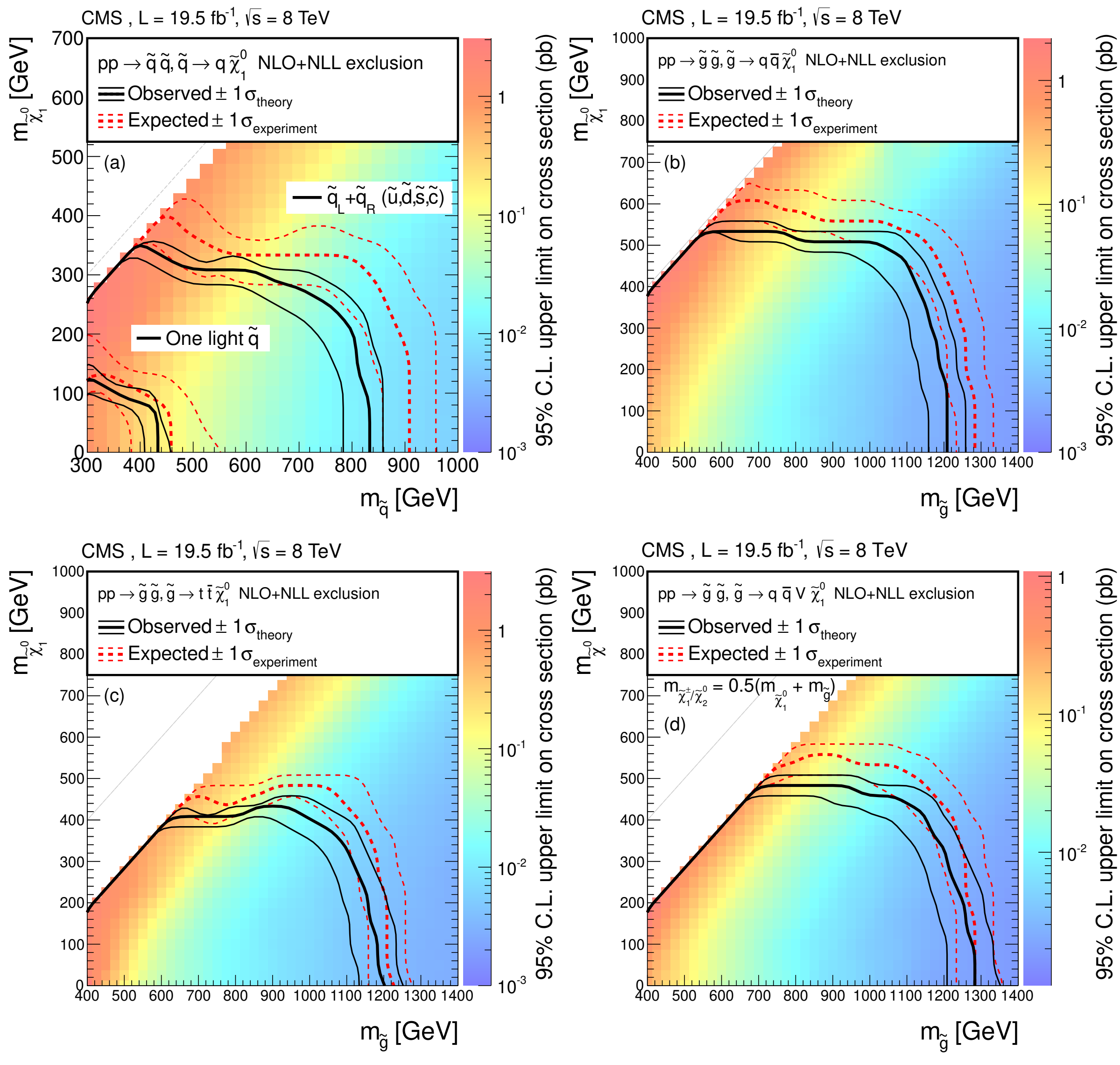

Figure 7: The observed and expected 95% CL upper limits on the (a) $\tilde{q}\tilde{q}$ and (b-d) $\tilde{g}\tilde{g}$ production cross sections in either the $(m_{\tilde{q}}, m_{\tilde{\chi}_1^0})$ or the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ plane obtained with the simplified models. For the $\tilde{q}\tilde{q}$ production the upper set of curves corresponds to the scenario when the first two generations of squarks are degenerate and light, while the lower set corresponds to only one light accessible squark.

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